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Measurement of the Properties of the top Quark at DØ

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Abstract. Different measurements of the properties of the *top* quark using up to 5.4 fb^{-1} collected with the DØ detector at the Fermilab Tevatron collider are presented. The top mass is obtained from a study of dilepton and lepton+jets final states, while the width is obtained from a combination of the measurements of the single *top* production via *t*-channel exchange and the determination of the $t \rightarrow Wb$ branching ratio. Furthermore the measurement of the helicity of the *W* boson from *top* quark decays, a measurement of $t\bar{t}$ spin correlations and a measurement of the jet pull (color flow) in $t\bar{t}$ events are presented.

Keywords: Tevatron, D0, top quark, properties, mass, spin, asymmetry

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INTRODUCTION

The *top* quark is the heaviest known elementary particle and was discovered at the Tevatron collider in 1995 [1, 2] at a mass of around 175 GeV. The dominant production channel at the Tevatron in $p\bar{p}$ collisions is via $q\bar{q}$ annihilation with 85% as opposed to gluon-gluon fusion which contributes only 15%. Many details of the analysis method and final results refer to the decay channel of the $t\bar{t}$ pair, i.e. if either none, one or both of the *W* bosons (stemming from decay of the *top* quarks) decay semi-leptonically. The dominant decay channel is the "all jets" channel, followed by the "lepton+jets" channel (l +jets) and the "dilepton" channel. The reason for these categories is the drastic change in amount of background in each of the channels with the "all jets" being worst. The l +jets channel is a good compromise between signal and background contribution whilst having high event statistics, whereas the "dilepton" channel has very small backgrounds but also reduced event statistics due to the small branching fractions.

MEASUREMENT OF TOP PROPERTIES

In the following recent measurements of the properties of the *top* quark in the l +jets and dilepton decay channel at DØ are summarized. First common analysis issues as well as systematics are briefly discussed. The main background contribution in the l +jets decay channel originates from W +jets production whereas the dilepton decay channel suffers most from contributions from Z +jets production.

The dominant systematic error sources for measurements of top properties are the

uncertainty of the jet energy scale (JES) and resolution, modeling of the signal and production including hadronization, higher orders and also the choice of the parton density distribution functions. Depending on the analysis also the systematic error of the b-tagging efficiency plays a major role.

Top Quark Mass

The first presented measurement is the latest *top* quark mass measurement by DØ. It uses the so-called matrix element method (ME) which calculates an event probability density from differential cross sections and detector resolutions. The transfer-function relates the probability density of measured quantities to the partonic quantities. As one of the *W* bosons decays hadronically a constraint on the *W* mass can be used to fit the jet energy scale in-situ. Figure 1(a) shows the JES against the *top* mass. The currently most precise DØ mass measurement uses 3.6 fb^{-1} and yields a mass of $m_t = 174.9 \pm 0.8(\text{stat.}) \pm 1.2(\text{sys.} + \text{JES}) \text{ GeV}$ [3].

The *top* mass is also measured from events in the dilepton decay channel using the

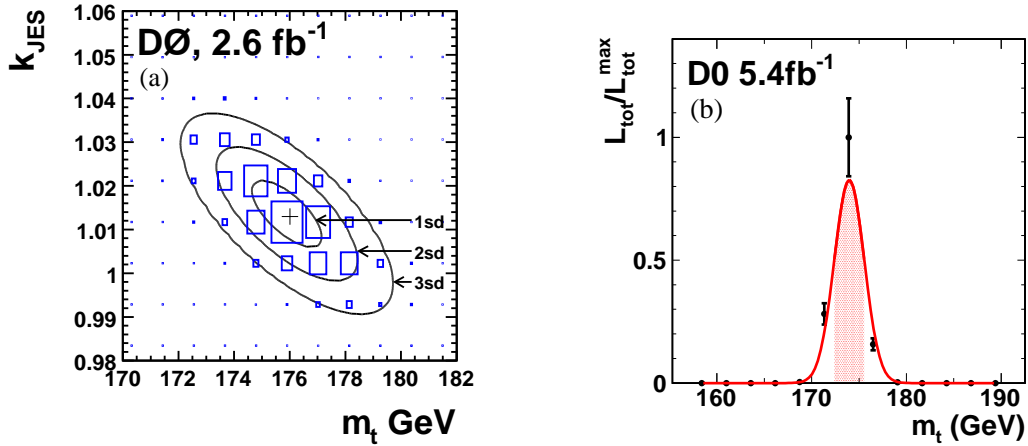


FIGURE 1. Fitted contours of equal probability for the two-dimensional likelihood as a function of k_{JES} against m_t (a) with the best fit and 1, 2 and 3 standard deviation contours for the l +jets decay channel. The calibrated and normalized likelihood for data (b) as a function of m_t with best estimate as well as 68% confidence level region marked by the shaded area for the dilepton decay channel.

matrix element method. This sample is limited in statistics due to the small BR but has very low backgrounds. There is no in-situ JES correction possible as both *top* quarks decay leptonically. Figure 1(b) shows the calibrated and normalized likelihood for data using 5.4 fb^{-1} . The measurement yields $m_t = 173.6 \pm 1.8(\text{stat.}) \pm 2.5(\text{sys.}) \text{ GeV}$ [4]. Furthermore the very same event selection as for the *top* mass measurement in the l +jets channel has been used to measure the mass difference ΔM_t between *top* and anti-*top* quarks (see Figure 2). The mass difference is predicted to be 0 in the standard model (SM). The analysis yields $\Delta M_t = 0.8 \pm 1.8(\text{stat.}) \pm 0.8(\text{sys.}) \text{ GeV}$ and does not show any indication of a *top* anti-*top* mass difference [5].

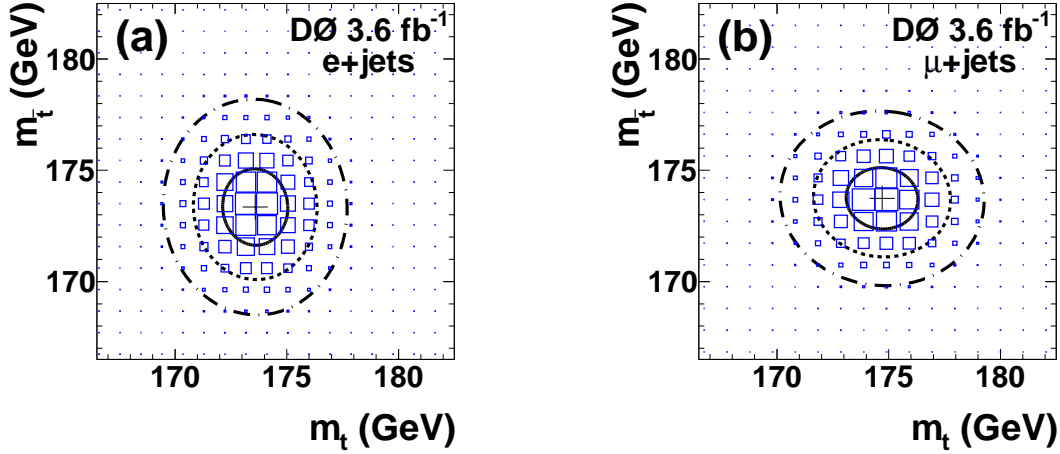


FIGURE 2. Combined likelihoods of the RunIIa and RunIIb measurements as functions of m_t and $m_{\bar{t}}$ in data for the (a) e +jets and (b) μ +jets channel. The solid, dashed, and dash-dotted lines represent the 1, 2, and 3 SD contours.

Top Decay Width

The indirect measurement of the decay width of the top quark uses two preceding measurements, that is the t -channel single top production cross section and the measurement of the ratio of the branching fractions $t \rightarrow Wq$ [15]. Using theoretical calculations and the measured t -channel cross section (see Figure 3(a)) the partial decay width $\Gamma(t \rightarrow Wb)$ can be determined:

$$\Gamma(t \rightarrow Wb) = \sigma(t\text{-channel}) \frac{\Gamma(t \rightarrow Wb)_{\text{SM}}}{\sigma(t\text{-channel})_{\text{SM}}} . \quad (1)$$

The total decay width Γ_t of the top quark is given by:

$$\Gamma_t = \frac{\Gamma(t \rightarrow Wb)}{B(t \rightarrow Wb)} . \quad (2)$$

By correcting the partial decay width with the result of the measurement of the ratio of the branching fractions $t \rightarrow Wq$: $\text{BR}(t \rightarrow Wb) = 0.97^{+0.09}_{-0.08}$ the total width of the top quark is measured to be $1.99^{+0.69}_{-0.55}$ GeV (see Figure 3(b)) [6]. This is the most precise indirect determination of the total decay width of the top quark. The value translates into a lifetime of $(3.3^{+1.3}_{-0.9}) \times 10^{-25}$ s.

W helicity

The $V - A$ nature of the weak force gives rise to a prediction for the polarization of W bosons originating from top quark decays. The standard model (SM) predictions for left-handed, longitudinal and right-handed polarizations are: $f_0 = 0.698$, $f_- = 0.301$

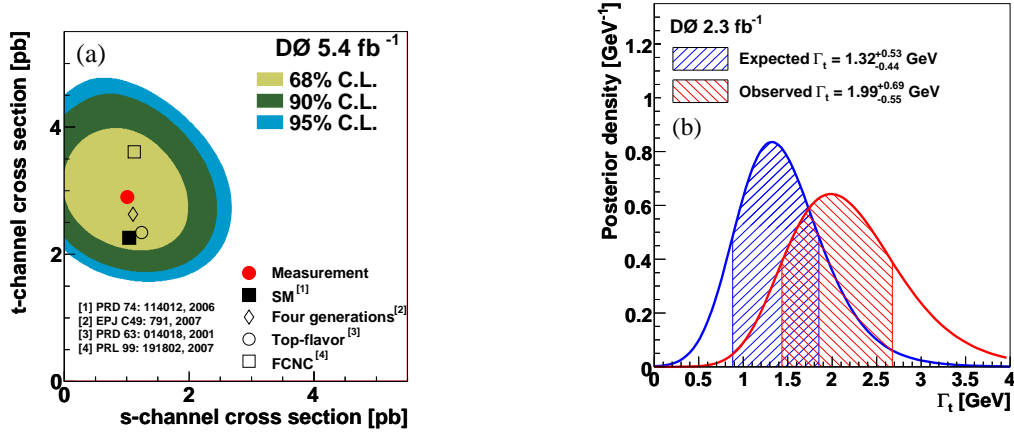


FIGURE 3. The result of the measurement of the single top production cross section in the s - and t -channel (a). The latter is used to determine the total width of the top quark (b).

and $f_+ = O(10^{-4})$ [8]. The measurement uses 5.4 fb^{-1} and the best fit values (see Figure 4(a)) are $f_0 = 0.669 \pm 0.078(\text{stat.}) \pm 0.065(\text{sys.})$ and $F_+ = 0.023 \pm 0.041(\text{stat.}) \pm 0.034(\text{sys.})$ [7] which is consistent with the standard model.

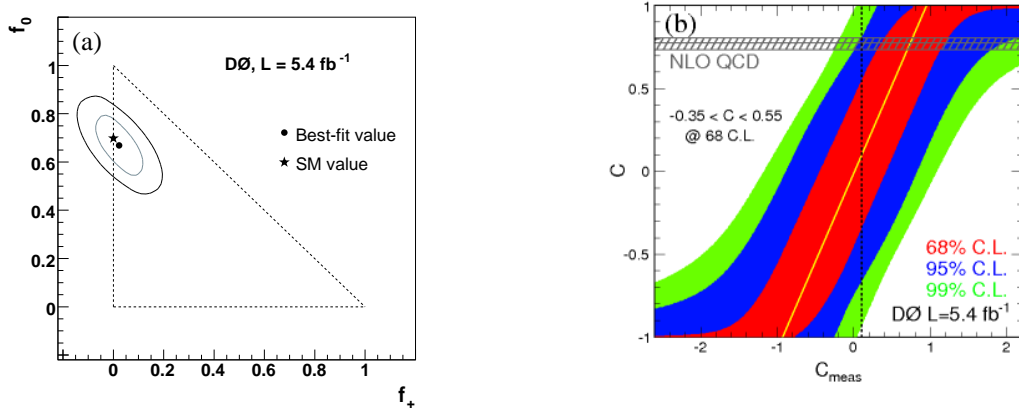


FIGURE 4. Result of the W boson helicity fit for the combined RunIIa and RunIIb data sample (a). The ellipses indicate the 68% and 95% C.L. contours, the dot shows the best-fit value, the triangle corresponds to the physically allowed region where $f_0 + f_+ \leq 1$, and the star marks the expectation from the SM. (b) shows the 68% (inner), 95% (middle), and 99% (outer) C.L. bands of C as a function of C_{meas} from likelihood fits to MC events for all channels combined. The vertical dashed black line depicts the measured value $C_{\text{meas}} = 0.10$. The horizontal band indicates the NLO QCD prediction of $C = 0.777^{+0.027}_{-0.042}$.

$t\bar{t}$ Spin correlations

A measurement that is complementary at the Tevatron as compared to the LHC because of the initial state is the measurement of spin correlations in $t\bar{t}$ events. The very

short lifetime of the top quark prevents spins from being affected by the fragmentation process. In other words the spin information is preserved and can affect the decay products, thus $t\bar{t}$ spin correlations are detectable. The next-to-leading (NLO) order QCD calculation predicts a correlation strength of $C = 0.78^{+0.03}_{-0.04}$ in the beam basis [9]. Figure 4(b) shows the result of the measurement using dilepton events in 5.4 fb^{-1} . A correlation strength of $C = 0.10 \pm 0.45$ (stat. + sys.) has been measured [10]. A new measurement uses events that decay in the dilepton decay channel and determines the fraction of $t\bar{t}$ events with spin correlation using a matrix element approach [11]. A correlation strength of $C = 0.57 \pm 0.31$ (stat. + sys.) has been measured.

Forward-backward Asymmetry A_{fb}

NLO QCD gives rise to a forward-backward asymmetry in $t\bar{t}$ events due to interference terms. Because of the initial state the measurement is different between $q\bar{q}$ (Tevatron) and qq (LHC). The asymmetry is larger at the Tevatron as the initial state is $q\bar{q}$ dominated as opposed to the LHC where it is gg dominated. The difference in rapidity $\Delta y = (y_t - y_{\bar{t}})$ between the two top quarks is a measure of the asymmetry A_{fb} given by:

$$A_{fb} = \frac{N^{\Delta y > 0} - N^{\Delta y < 0}}{N^{\Delta y > 0} + N^{\Delta y < 0}} . \quad (3)$$

Using 4.3 fb^{-1} a forward-backward asymmetry of $A_{fb} = 8 \pm 4(\text{stat.}) \pm 1(\text{sys.})\%$ is measured compared to the MC@NLO prediction of $(2.4 \pm 0.7)\%$. Recently this has been updated [12].

Color Flow

$t\bar{t}$ events provide a relatively clean source for hadronically decaying W bosons and can therefore be used to study the color flow in an event. Partons carry a color charge which provides additional information about the event. A color singlet like the Higgs decaying to $b\bar{b}$ will not be color-connected to the beam as the two b quarks stem from a color neutral object. A color octet like a gluon decaying to $b\bar{b}$ will be color-connected to the beam as the gluon carries a color by itself. Figure 5(a) shows a schematic drawing of this useful analysis technique using jet pull to study the color flow.

To show the validity of the method two different hypotheses for the hadronically decaying W bosons are assumed: SM $t\bar{t}$ with a color-singlet hadronically decaying W boson or $t\bar{t}$ with a color-octet hadronically decaying W' boson. f_{singlet} gives the fraction of events that originate from color-singlet W boson decays with a SM prediction of $f_{\text{singlet}} = 1$. Figure 5(b) shows the limit for f_{singlet} derived using 5.4 fb^{-1} : $f_{\text{singlet}} = 0.56 \pm 0.38(\text{stat.} + \text{sys.}) \pm 0.19(\text{MCstat.})$ [13].

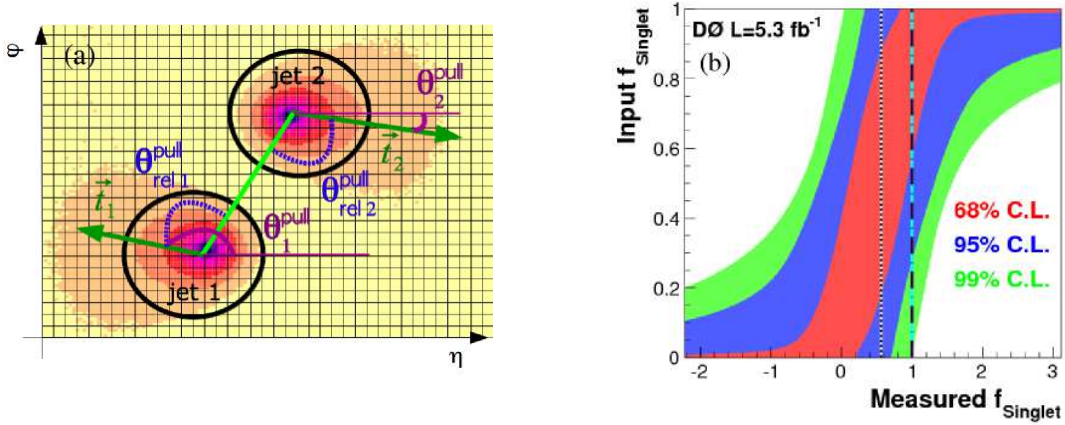


FIGURE 5. Schematic drawing (a) showing two jets in the $\eta - \phi$ plane, and the reconstruction of the jet pull vectors (\vec{t}), jet pull angles (θ_{pull}), and relative jet pull angles ($\theta_{\text{pull,rel}}$). (b) shows the expected C.L. bands for f_{Singlet} . The measured value is shown on the horizontal axis, and the input value on the vertical axis. The wide-dashed line shows the expected value and the black-white fine-dashed line indicates the measured value of f_{Singlet} .

CONCLUSION

A wealth of measurements of properties of the *top* quark at DØ have been discussed showing the great performance of the Tevatron and the DØ detector. All results are consistent with the standard model expectations. The final DØ data sample will have 2 – 3 times the presented statistics allowing for new & more precise results in the future.

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